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TECHNICAL NOTE

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HELIUM CONCENTRATIONS DOWNSTREAM OF A VENT EXHAUSTING HELIUM AT SONIC VELOCITY INTO A SUPERSONIC STREAM OF AIR AT MACH NUMBERS OF 3.51 AND 4.50

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SUMMARY

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Concentration profiles of helium have been measured at three axial stations downstream of a helium vent exhausting at sonic velocity into a supersonic stream of air. The sampling stations were located at 7.2, 14.4, and 21.7 vent diameters downstream of the vent. The tests were conducted at free-stream Mach numbers of 3.51 and 4.50, ratios of vent static pressure to free-stream static pressure from approximately 4 to 18, and helium stagnation temperatures of approximately 550° R and 260° R.

Increasing the ratio of vent pressure to free-stream pressure resulted in a general increase in the concentration profiles at all three measuring stations and a decrease in the rate of decrease with distance of the maximum measured concentration through 21.7 vent diameters downstream of the vent. Increasing the vented-gas stagnation temperature resulted in an increase in the rate of mixing of the vented gas and the ambient air.

INTRODUCTION

The use of liquid hydrogen or similar cryogenic fuels for current and future rocket motors has introduced the problem to the designer of disposing of the fuel vapor during the chill-down period of flight. If concentrations of hydrogen vapor between approximately 5 percent and 75 percent by volume should penetrate into the hot missile boundary layer or nozzle exhaust region, ignition of the vapor could occur and result in possible damage or even destruction of the vehicle. There are presently two approaches to the solution of this problem: (1) pipe the vapor to the base of the missile and vent it overboard, or (2) vent the vapor overboard locally on the side of the booster and assume that the turbulent mixing of the air and vented gas will reduce the concentration of the gas to such an extent that autoignition will not occur either in the boundary layer or in the nozzle exhaust region. The first solution is not too desirable because of the inherent weight penalty involved. The second solution does not present this weight handicap;

however, its relative merits cannot be fully assessed as a result of the limited amount of information available pertaining to the rate of mixing of a vented gas into a supersonic stream. This phenomenon is difficult to resolve theoretically, and the experimental approach has generally been plagued by difficulties encountered in instrumentation and technique.

As a result of this lack of information and the emphasis currently placed on this phenomenon, an experimental program is underway at the Langley Unitary Plan wind tunnel to isolate and define the parameters that affect vented-gas concentration profiles. A newly designed instrumentation system, as discussed in reference 1, has been utilized for determining the gaseous composition. Because of the relatively large vented-gas mass flows introduced into the closed-circuit tunnel, safety requirements necessitated the availability in large quantities of an inert gas having physical properties similar to those of hydrogen. These considerations led to the selection of helium as the vented gas.

Preliminary wind-tunnel tests have been completed in order to determine inherent problem areas associated with adapting the instrumentation to the wind-tunnel system and to obtain an insight into the governing parameters that affect the gaseous concentrations downstream of a simple vent configuration; the results of these preliminary tests are presented herein. The tests were conducted at tunnel Mach numbers of 3.51 and 4.50.

SYMBOLS

D — inside diameter of helium vent exit, 1.38 in.

M_∞ — free-stream Mach number

m_j — mass flow of vented gas (helium) per unit area, lb/sec-ft^2

m_∞ — mass flow of free-stream air per unit area, lb/sec-ft^2

p_j — vent-exit static pressure, lb/ft^2

p_∞ — free-stream static pressure, lb/ft^2

$p_{t,\infty}$ — free-stream stagnation pressure, lb/ft^2

$T_{t,j}$ — helium stagnation temperature, $^\circ$R

x — axial distance downstream of vent exit, in.

y — horizontal distance from vent axis of symmetry, in.

z — vertical distance perpendicular to vent axis of symmetry, in.

Subscript:

nom nominal values

MODEL

The installation of the model assembly and the composition survey rake in the high Mach number test section of the Langley Unitary Plan wind tunnel is illustrated in figures 1 and 2. The vent model was attached to a flat plate by an airfoil support structure and consisted of a cylindrical pipe which had a blunt nose. (See fig. 2.) A pitot-static tube was located in the vent exit to measure the local static and stagnation pressures and also to determine the vent-exit Mach number. The flat-plate surface was 18 inches by approximately 57 inches and had a swept wedge leading edge. The local gas compositions downstream of the vent were obtained with a 13-tube mechanically driven total-head rake, also illustrated in figure 2. The rake could be roll oriented to either the vertical or the horizontal plane. The rake was positioned at 10, 20, and 30 inches downstream of the vent, or, in terms of vent diameters, the measurements were obtained at 7.2 vent diameters, 14.4 vent diameters, and 21.7 vent diameters. An additional tube was located on the plate leading edge to determine the percent of helium concentration due to the recirculation of the tunnel air. The helium stagnation temperature was measured with a probe installed in the support strut. (See fig. 2.)

INSTRUMENTATION

The instrumentation apparatus for analyzing the gas samples is discussed in detail in reference 1, thus only a cursory description will be presented here. The primary components of the system shown schematically in figure 3 are an ionization (sampling) chamber, an ionization gage, a diaphragm pressure gage, and a ratio meter.

The flow of the helium-air mixture from a given total-head tube on the rake was maintained throughout the sampling chamber with a mechanical vacuum pump. The pressure in the sampling chamber was controlled to within the operational range of the ionization gage (1 to 30 mm Hg) and diaphragm pressure gage (0 to 50 mm Hg) by adjusting two throttling values. The electrical output of the ionization gage is proportional to the percent of helium concentration in the sampling chamber at a given chamber pressure which was measured with the diaphragm pressure gage. Previous laboratory experiments have shown that after suitable amplification, such that unit output of the ionization gage corresponds to unit output of the pressure gage in 100-percent air, the ratio of the electrical outputs of the ionization and diaphragm pressure gages in a mixture of helium and air is proportional to the percent of helium concentration and is independent of the pressure in the sampling chamber. Therefore, the ratio meter, a null-seeking servo system, was added to the system to obtain this ratio. Because the output in counts of the instrumentation system was directly proportional to the percent of helium concentration, the following single linear equation for determining the helium concentrations resulted:

$$\text{Percent helium} = A(\text{counts}) + B$$

The constants A and B were determined prior to the test with the use of known concentrations of helium and air mixtures.

A sufficient number of the instrumentation components, excluding the ratio meter, were available such that there was a unique instrumentation system for each total-head tube. Inasmuch as only one ratio meter was available, the output of each system was manually switched to the ratio meter with a multiple-selector switch. In general, the time required for the ratio meter to stabilize with each system did not exceed 10 seconds. This period of 10 seconds for each of the 14 systems required approximately 2 minutes to make a complete span for each set of test conditions.

The helium supply system is shown schematically in figure 4. The helium mass flow was controlled by adjusting the flow-regulator valve at a given supply pressure until the differential pressure was obtained across the orifice plate to correspond to the desired mass flow based on a pretest calibration.

The outputs of the supply pressure transducer, capable of 0 to 1,000 lb/sq in., and of the differential pressure transducer, capable of 0 to 5 lb/sq in., were recorded simultaneously with each recording from the ratio meter to insure that the helium variables remained constant throughout a given run. For the low-temperature-helium runs, the helium was forced through a tubular coil submerged in a Dewar vessel filled with liquid nitrogen. The helium temperature was measured with a stagnation temperature probe located in the support assembly, as shown in figure 2.

APPARATUS AND TEST CONDITIONS

The tests were conducted in the high Mach number test section of the Langley Unitary Plan wind tunnel described in reference 2. The tunnel has an asymmetrical sliding-block nozzle which permits a continuous variation in test-section Mach number from 2.30 to 4.65.

The tests were conducted at Mach numbers of 3.51 and 4.50 at free-stream Reynolds numbers per foot from 0.6×10^6 to 2.8×10^6. The helium mass flow was varied from 0.02 lb/sec to 0.04 lb/sec and the stagnation temperature was varied from approximately 550° R to 260° R. The tunnel stagnation temperature was held constant at 630° R.

ACCURACIES

As discussed in reference 1, the accuracy of the instrumentation system alone based on a pretest laboratory checkout was ±0.3 percent. Additional errors occur during the wind-tunnel test, however, as a result of rake deflection, contamination of tunnel air, and so forth. In order that the accuracies for the complete wind-tunnel installation be determined, results of the center tube of the rake for the same test conditions were compared with the rake in the vertical and in the horizontal planes, the center tube remaining at the same location in the tunnel. The repeatability obtained with this technique was very sensitive to both helium mass flow and the rake axial position. The largest deviation of 3 percent occurred with the rake in the most forward position $(x/D = 7.2)$ and at the lowest value of m_j/m_∞. This large deviation is attributed to a slight deflection of the rake support strut because of asymmetrical aerodynamic loading in a region of a very large concentration gradient. The best repeatability was approximately 1 percent and was obtained at the highest helium mass flow where the concentration gradients in the region of the center tube were relatively small.

RESULTS AND DISCUSSION

The measured concentration profiles in the vertical plane of symmetry throughout the test range of p_j/p_∞ are presented in figure 5 for a constant helium stagnation temperature at Mach numbers of 3.51 and 4.50. The effect of helium stagnation temperature on the concentration profiles is shown in figure 6 at a Mach number of 3.51, and the effect of p_j/p_∞ on the concentration profiles at $M_\infty = 4.50$ in the horizontal plane 0.25 inch below the jet center line of symmetry is shown in figure 7. As shown in the keys of figures 5, 6, and 7, the variables for this investigation at constant Mach number and helium stagnation temperature are p_j/p_∞, m_j/m_∞, and $p_{t,\infty}$. The variable p_j/p_∞ was selected for most of the discussion herein for two reasons: (1) the interdependence of this variable and m_j/m_∞ and (2) the general application of this variable in previous publications pertaining to jet flow.

At $M_\infty = 3.51$ (fig. 5(a)), an increase of p_j/p_∞ through a range from 4.3 to 17.3 resulted in a general increase in the concentration profiles and the jet spreading at each of the three sampling stations. For ratios of jet to free-stream pressure of 4.5 and 8.6, the jet-boundary location in the vertical plane of symmetry remained within the sampling region of the survey rake for all three sampling stations. At $p_j/p_\infty \approx 17.1$, the upper jet boundary (plate side of the vent) extended beyond the rake survey region and is initially indicated by the experimental data at $x/D = 14.4$. The lower jet boundary at $p_j/p_\infty \approx 17.1$ remained within the rake survey region for the first two sampling stations; however, at $x/D = 21.7$ the boundary is in the immediate vicinity of the bottom survey tube.

The effect of the same approximate range of p_j/p_∞ on the concentration profiles at $M_\infty = 4.50$ is shown in figure 5(b). The same general trend in the variation of the concentration profiles with p_j/p_∞ as obtained at $M_\infty = 3.51$ is shown at the higher Mach number. A comparison of the data at the two Mach numbers indicates a larger divergence of the lower jet boundary and a smaller divergence of the upper jet boundary at the same p_j/p_∞ for the higher Mach number. Because of this combined effect at $M_\infty = 4.50$, the location of the upper jet boundary remains within the rake survey region even to the point $x/D = 21.7$ and the lower jet boundary extends beyond the survey region at $x/D = 21.7$.

The effect on the concentration profiles of decreasing the helium stagnation temperature from approximately 550° R to 260° R is presented in figure 6 at $M_\infty = 3.51$. Maintaining a constant value of p_j/p_∞ for a given mass flow at the two temperatures required a change in the tunnel stagnation pressure which introduces secondary wake effects, to be discussed subsequently. However, the effect of decreasing the helium temperature as shown in figure 6 is somewhat greater than this $p_{t,\infty}$ effect and consists of a decrease in the rate of mixing of helium and ambient air or an increase in the magnitude of the concentration profiles.

The concentration profiles in the horizontal plane 0.25 inch below the jet center line are shown in figure 7 for $M_\infty = 4.50$ and for $p_j/p_\infty \approx 4.5$ and 17.0. At $p_j/p_\infty \approx 4.4$, the concentration profiles indicate a maximum helium concentration on each side of the vertical plane of symmetry, the magnitude of this maximum concentration decreasing with increasing distance downstream of the vent. The decrease in the concentrations on the jet center line at all three stations is attributed to the wake formed by the pitot tube in the vent exit. Immediately downstream of this tube a low-pressure region occurs allowing the air to vent into the core of the region of high helium concentration. This effect, as would be expected, is very sensitive to helium mass flow as shown in figure 7; that is, the percent reduction of helium concentration in the wake of the pitot tube decreases with increasing mass flow.

In order to obtain the range of p_j/p_∞ presented in figures 5, 6, and 7, it was necessary to vary both the helium supply pressure and the tunnel stagnation pressure $p_{t,\infty}$. The latter method of increasing p_j/p_∞ introduces secondary effects on the concentration profiles associated with the wake formation aft of the vent support strut and the vent-exit pitot tube, as can be seen in the schlieren photographs of figure 8. In order to determine the extent of these secondary effects, the values of m_j and $p_{t,\infty}$ were varied such that the value of p_j/p_∞ remained approximately constant at a value of 8.6. This effect at a Mach number of 3.51, shown by the open and solid squares in figure 5(a), is small, thus indicating the dependence of the concentration profiles on p_j/p_∞. This effect of $p_{t,\infty}$ at $M_\infty = 4.50$ (open and solid squares in fig. 5(b)) is much larger than at $M_\infty = 3.51$ and must be considered when determining the effect of p_j/p_∞ in those cases in which $p_{t,\infty}$ was varied. The effect associated with $p_{t,\infty}$ at $M_\infty = 4.50$

can also be attributed partially to the vortex, located between the vent model and plate shown in figure 8(b), emanating from the intersection of the plate leading-edge shock and the model bow shock. (This vortex is not to be confused with the dark spot on the photograph.)

A summary of the maximum measured helium concentrations in the vertical plane downstream of the vent at each of the three axial stations is presented in figure 9 for $M_\infty = 3.51$ and 4.50, for $T_{t,j} = 260^\circ$ R and 550° R, and throughout the range of p_j/p_∞. At $M_\infty = 3.51$ (fig. 9(a)), where the tunnel stagnation pressure for a constant p_j/p_∞ has a very small effect on the concentration profiles, the rate of decrease in the maximum helium concentrations decreases with increasing p_j/p_∞. This decrease at $x = 30$ inches or $x/D = 21.7$ was approximately 36 percent at $p_j/p_\infty \approx 4.5$ as compared with 8 percent for $p_j/p_\infty \approx 17$. Similar trends are shown at $M_\infty = 4.50$; however, the inherent stagnation pressure effects at this Mach number complicate the effects associated with the various independent parameters.

The summary figure of the effect of $T_{t,j}$ (fig. 9(b)) indicates the largest effect of $T_{t,j}$ on the maximum measured concentrations at the lowest value of p_j/p_∞. At $x = 30$ inches or $x/D = 21.7$, for $p_j/p_\infty \approx 4.7$, the maximum measured values were reduced approximately 14.5 percent as a result of an increase in $T_{t,j}$ from 260° R to 550° R, whereas, there is only an 8-percent reduction at $p_j/p_\infty \approx 8.4$. The maximum measured concentrations at 7.2 diameters or 10 inches downstream of the vent were apparently unaffected throughout the full range of variables at both Mach numbers.

Throughout the range of variables presented herein, the major portion of the helium concentration profiles at 21.7 vent-exit diameters downstream of the vent are within the range of flammability limits for a corresponding mixture of hydrogen vapor and air as presented in reference 3. Although optimization of vent designs was not the objective of this investigation, the potentially hazardous gas concentrations obtained indicate the desirability of conducting such an experimental investigation with the sampling range downstream of the vent extended to much larger values of x/D.

SUMMARY OF RESULTS

An experimental investigation in which concentration profiles of helium were measured downstream of a helium vent exhausting at sonic velocity into a supersonic stream of air indicated the following results:

1. Increasing the ratio of vent pressure to free-stream pressure resulted in a general increase in the concentration profiles at all three sampling stations downstream of the vent - 7.2, 14.4, and 21.7 vent diameters. An increase of this

ratio also decreases the rate of decrease with distance of the maximum measured concentration for all three sampling stations.

2. Increasing the vented-gas stagnation temperature resulted in an increase in the rate of mixing of the vented gas and the free-stream air.

3. Throughout the range of variables tested, the major portion of the helium concentration profiles at 21.7 vent-exit diameters downstream of the vent were within the range of flammability limits for a corresponding mixture of hydrogen vapor and air.

Langley Research Center,
National Aeronautics and Space Administration,
Langley Station, Hampton, Va., February 15, 1963.

REFERENCES

1. Melfi, Leonard T., Jr., and Wood, George M., Jr.: The Use of an Ionization Gage as a Quantitative Analyzer for Bi-Gaseous Mixtures. NASA TN D-1597, 1962.

2. Anon.: Manual for Users of the Unitary Plan Wind Tunnel Facilities of the National Advisory Committee for Aeronautics. NACA, 1956.

3. Drell, Isadore L., and Belles, Frank E.: Survey of Hydrogen Combustion Properties. NACA Rep. 1383, 1958. (Supersedes NACA RM E57D24.)

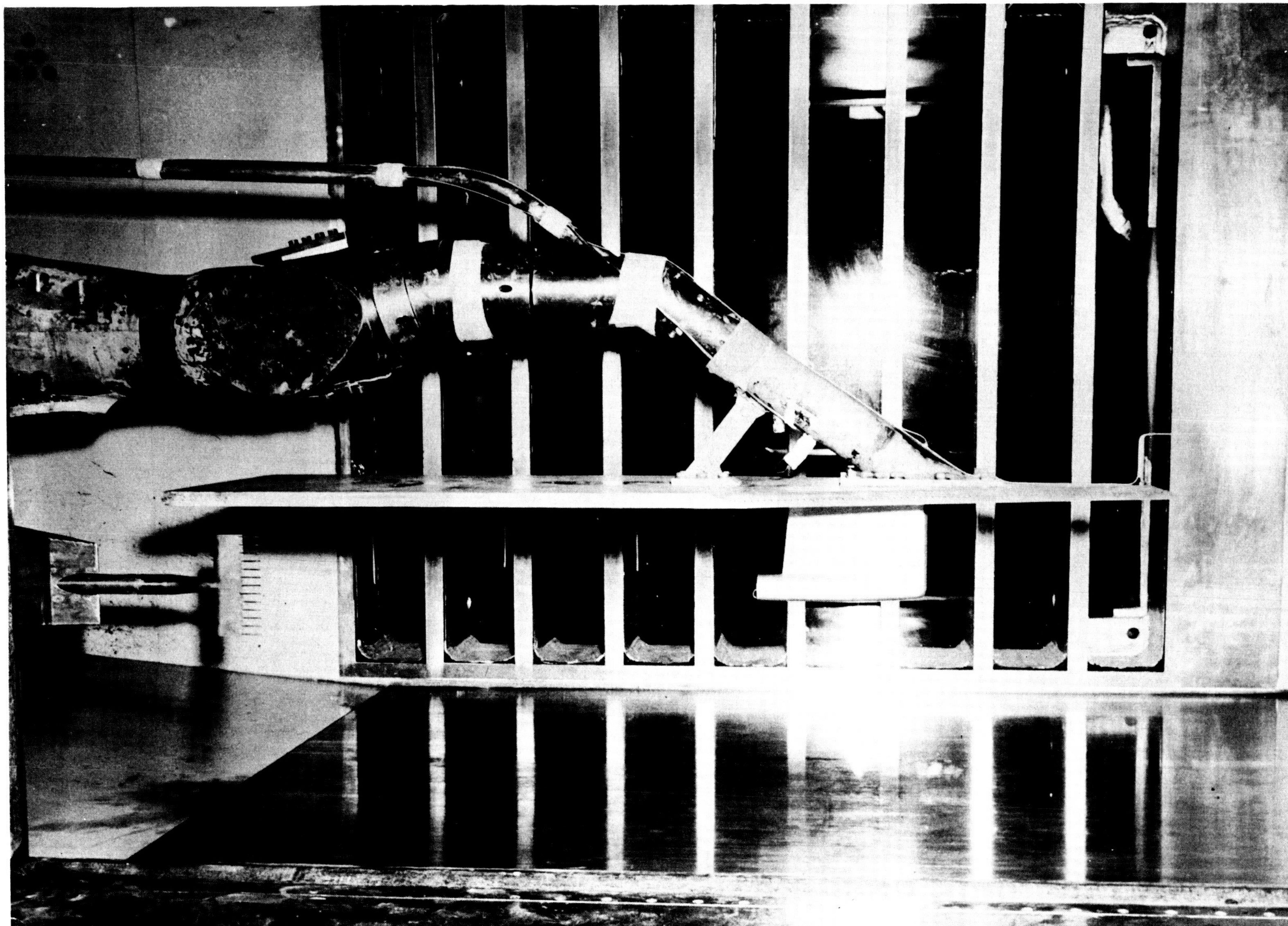


Figure 1.- Installation of model in test section. L-62-4924

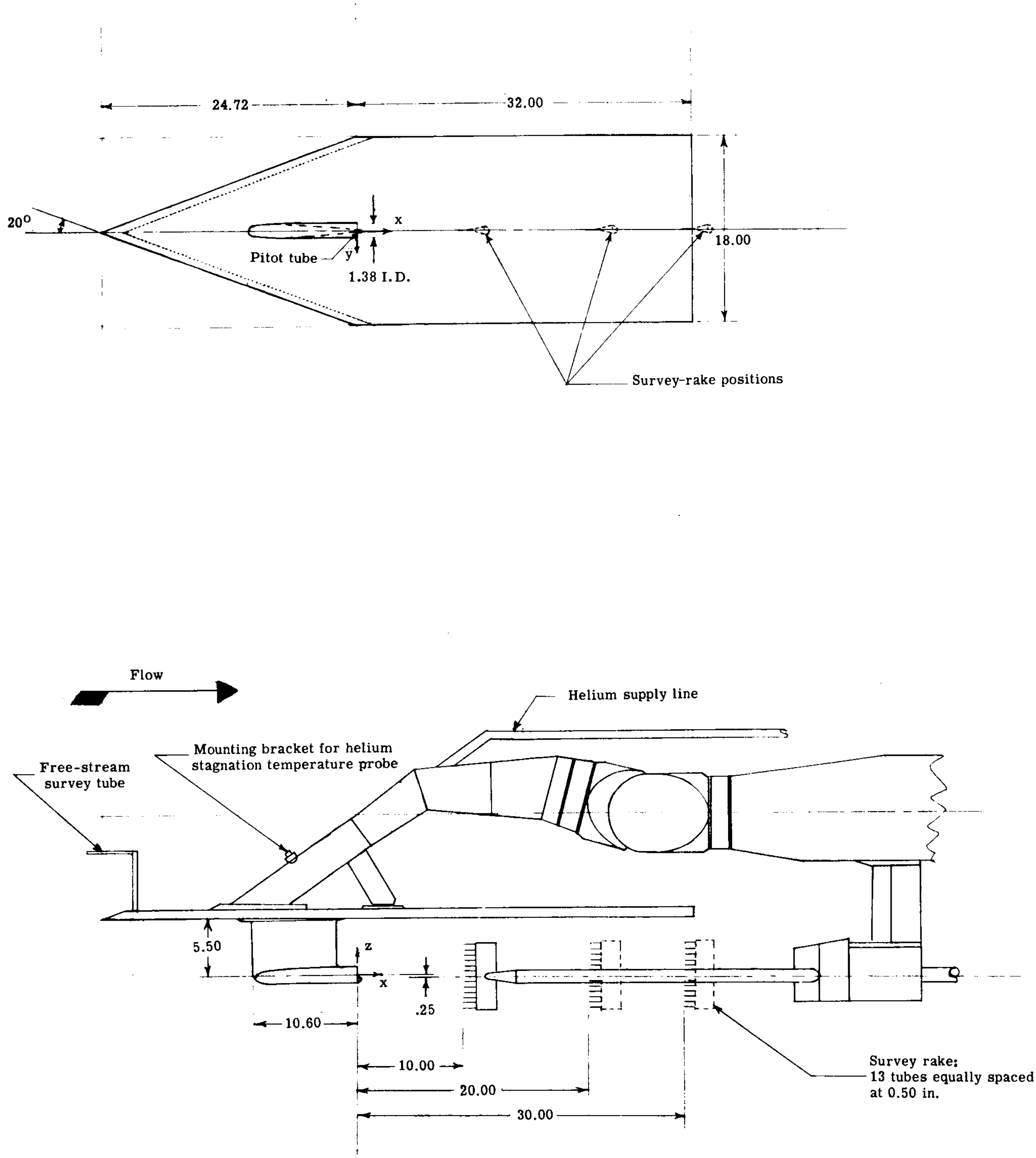


Figure 2.- Drawing of model installation showing survey-rake locations. (All dimensions are in inches unless otherwise indicated.)

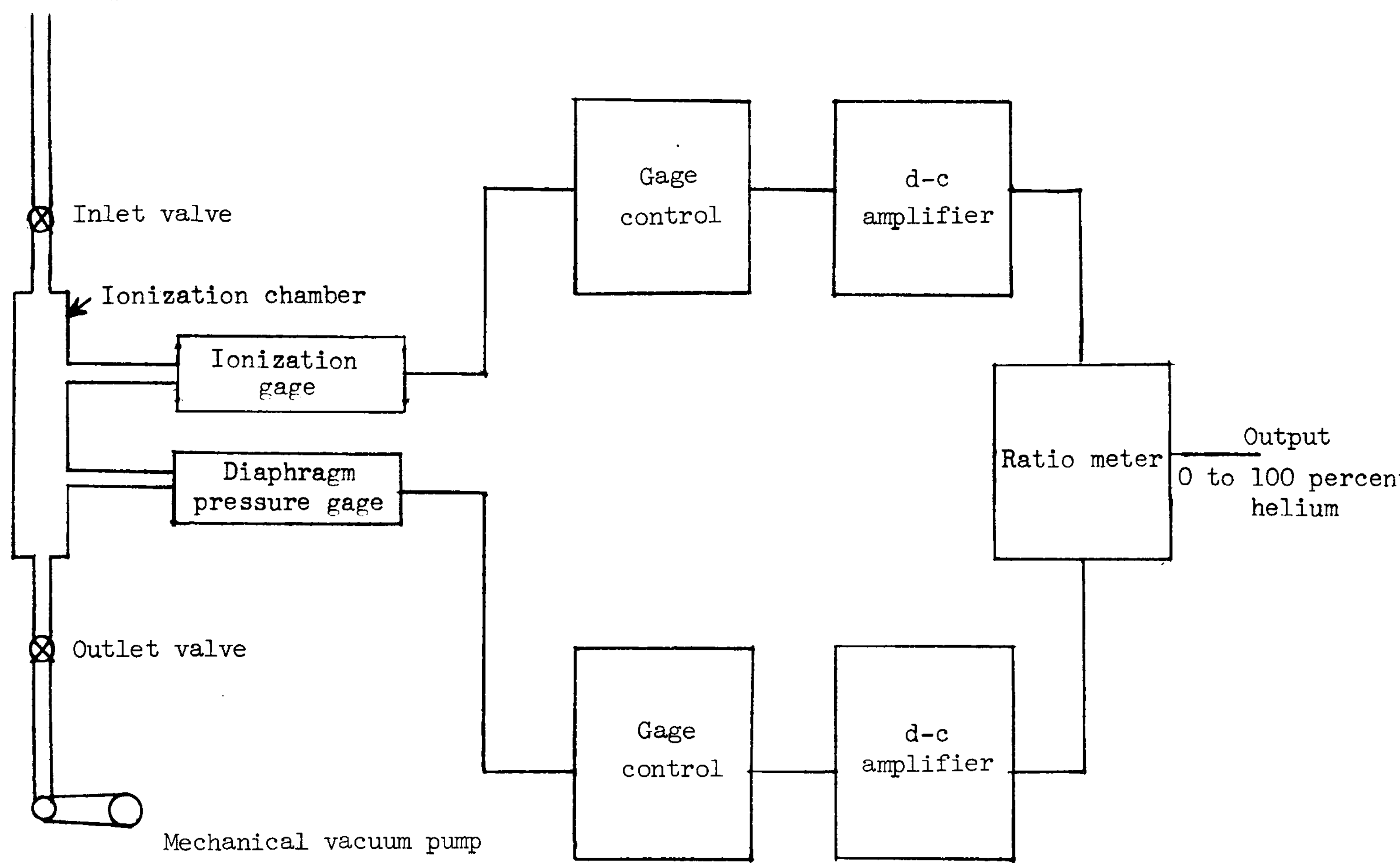


Figure 3.- Block diagram of instrumentation system.

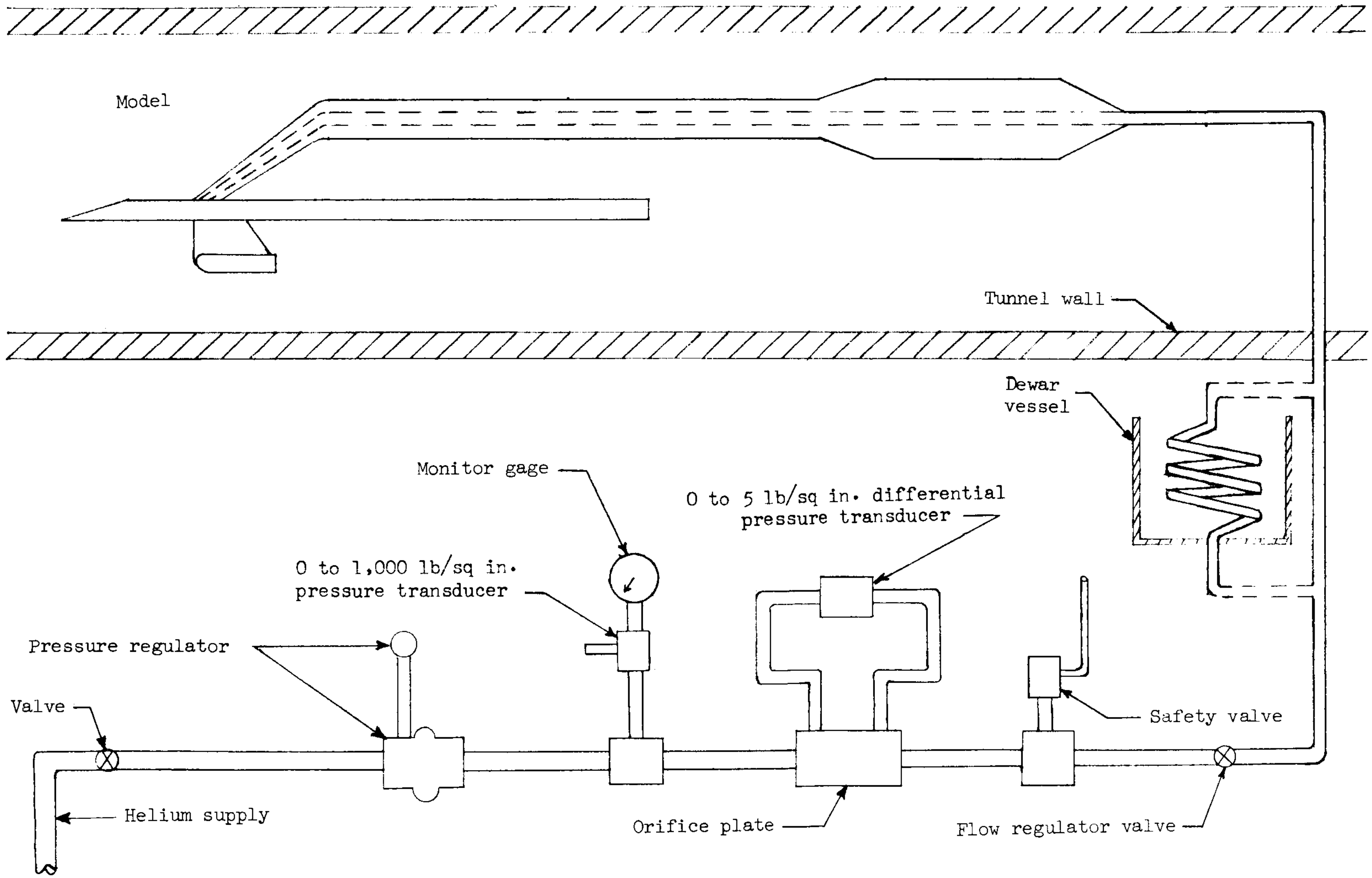
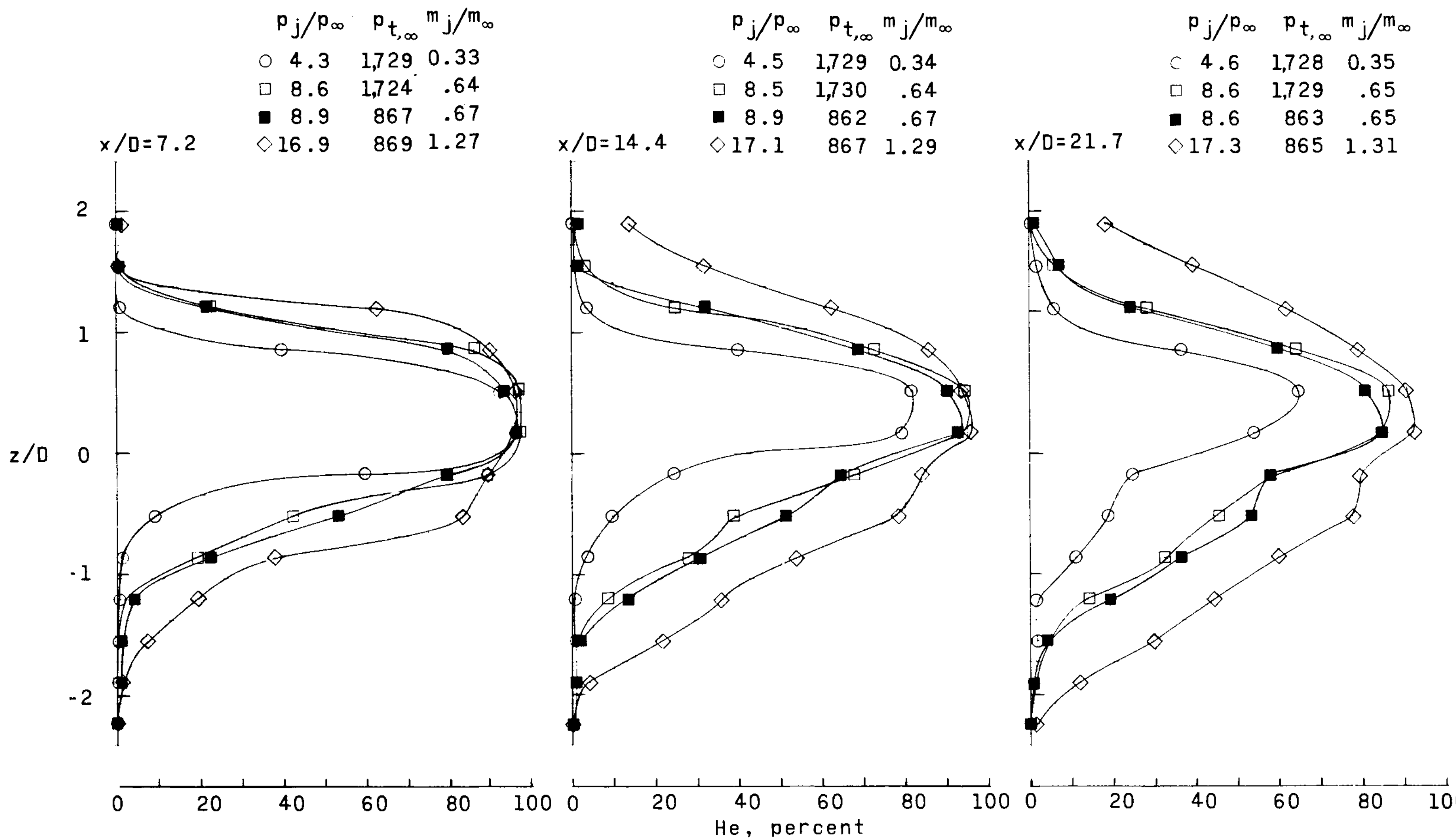
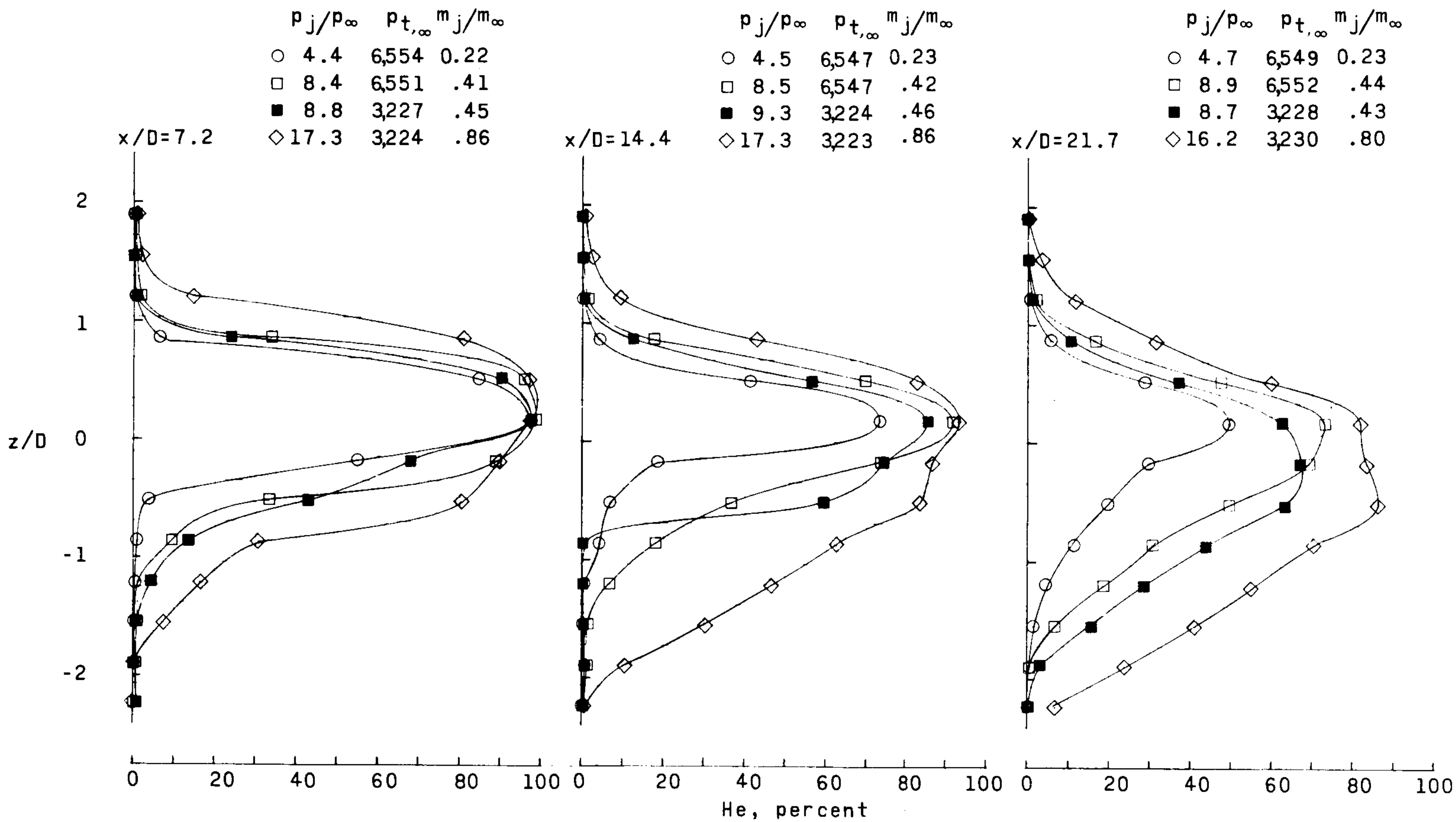


Figure 4.- Helium supply system.



(a) $M_\infty = 3.51$.

Figure 5.- Effect of p_j/p_∞ on concentration profiles in vertical plane of symmetry. $T_{t,j} \approx 550^\circ$ R.



(b) $M_\infty = 4.50$.

Figure 5.- Concluded.

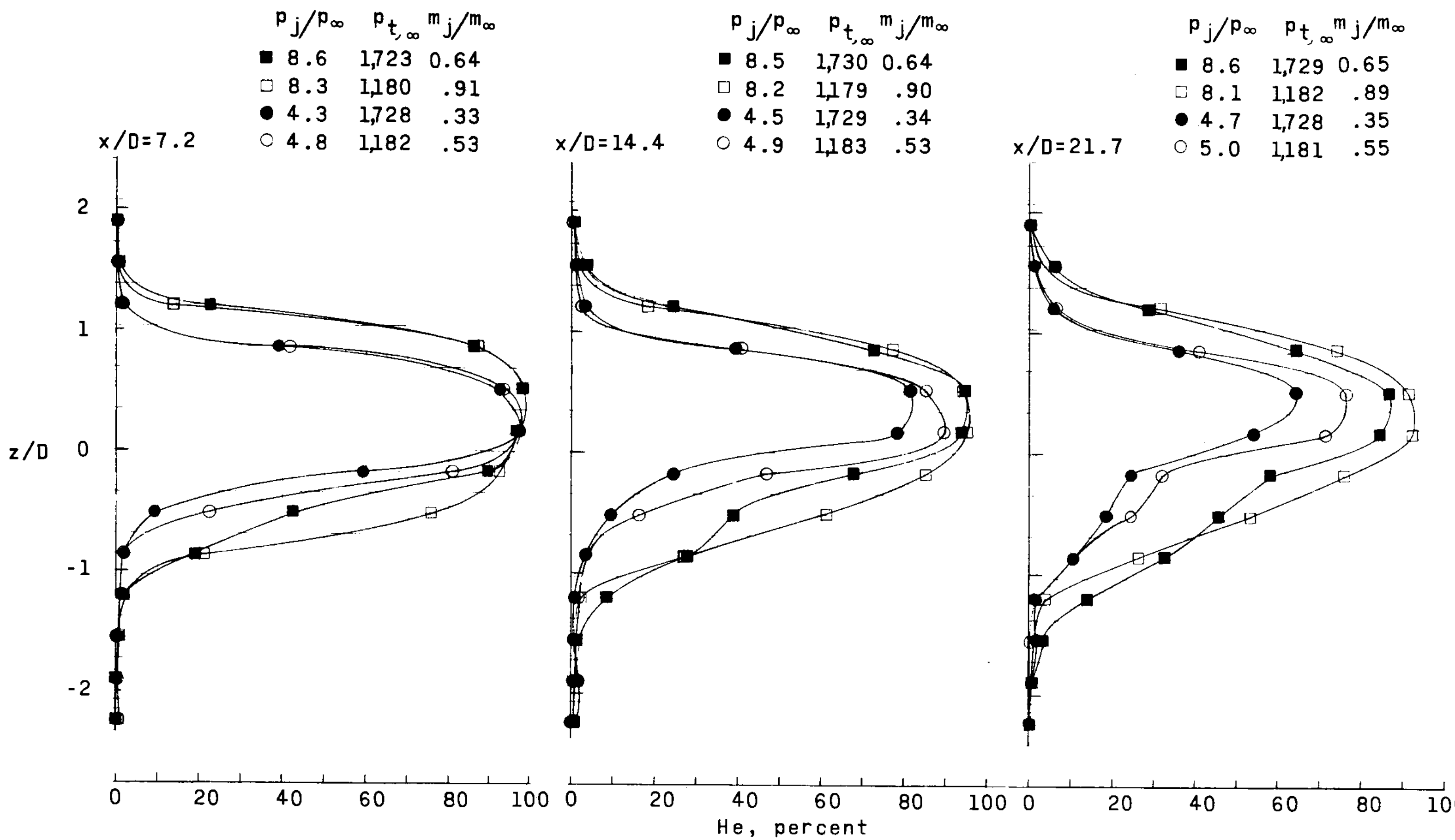


Figure 6.- Effect of helium stagnation temperature on concentration profiles in vertical plane of symmetry. Solid symbols denote $T_{t,j} \approx 550^\circ$ R; open symbols denote $T_{t,j} \approx 260^\circ$ R. $M_\infty = 3.51$.

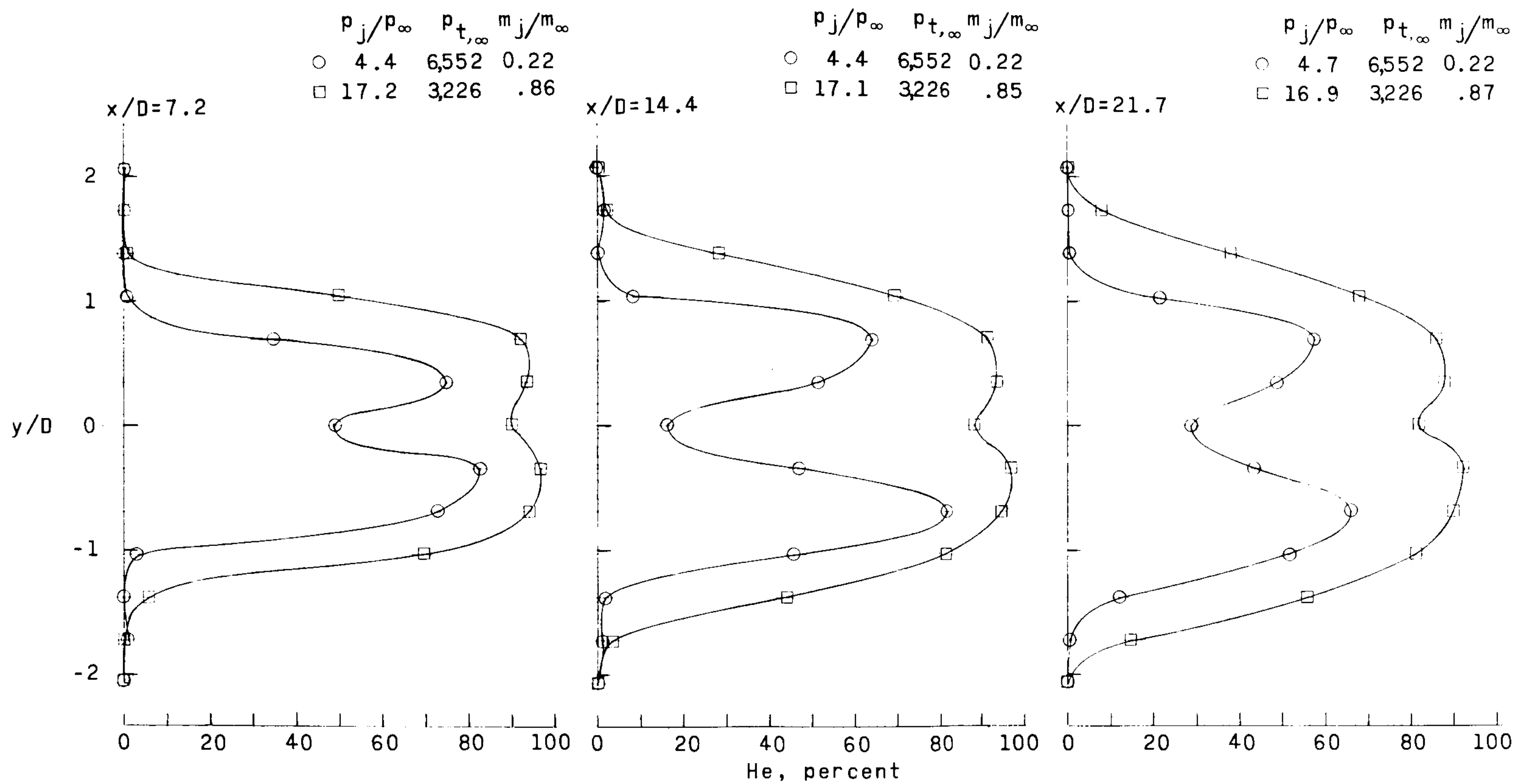
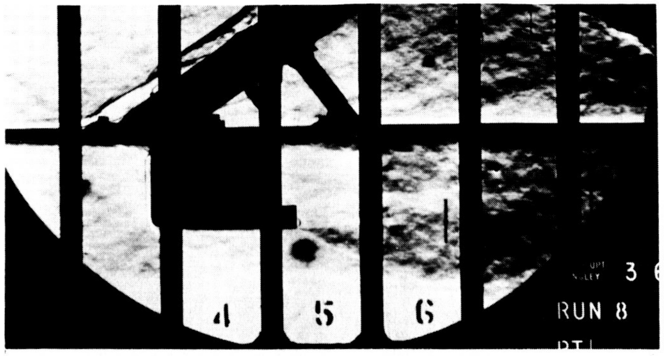
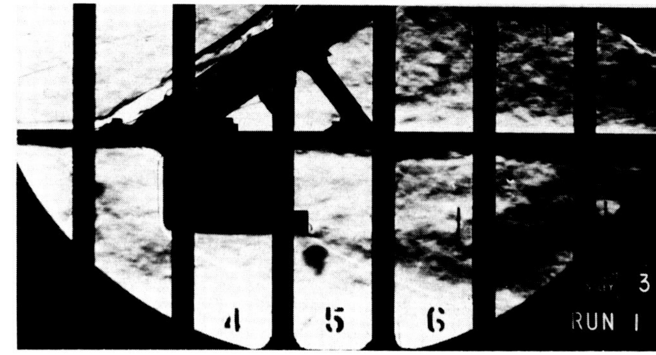


Figure 7.- Effect of p_j/p_∞ on concentration profiles in horizontal plane 0.25 inch below jet center line. $M_\infty = 4.50$; $T_{t,j} \approx 550^\circ$ R.

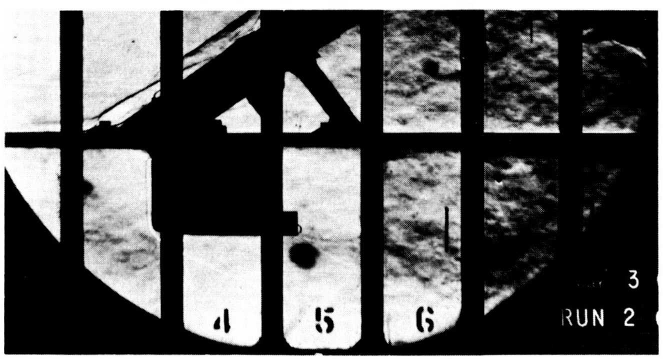


$p_{t,\infty} = 1{,}728$

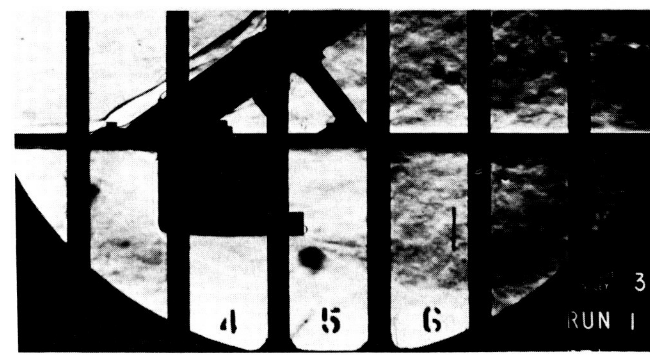


$p_j/p_\infty = 4.7$
$m_j/m_\infty = 0.35$

$p_j/p_\infty = 8.6$
$m_j/m_\infty = 0.65$



$p_{t,\infty} = 864$



$p_j/p_\infty = 8.6$
$m_j/m_\infty = 0.65$

$p_j/p_\infty = 17.4$
$m_j/m_\infty = 1.31$

(a) $M_\infty = 3.51$.

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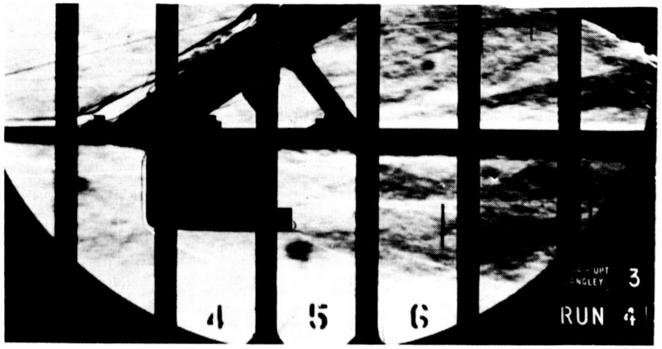
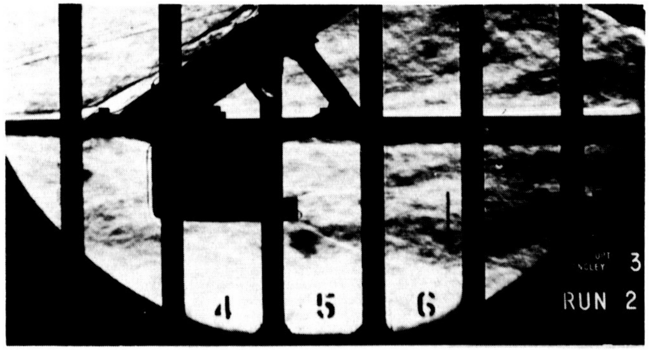
Figure 8.- Typical schlieren photographs.

$p_{t,\infty} = 6{,}552$

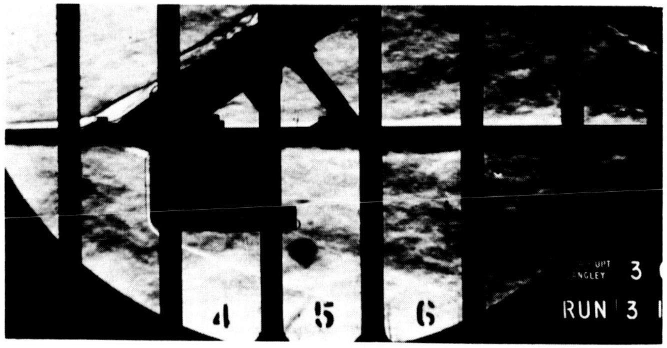


$p_j/p_\infty = 4.7$
$m_j/m_\infty = 0.23$

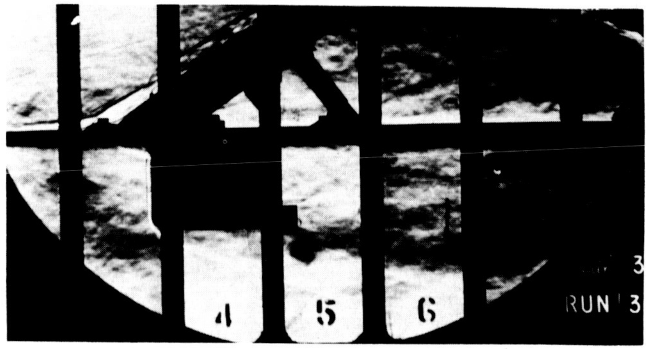


$p_j/p_\infty = 8.5$
$m_j/m_\infty = 0.42$

$p_{t,\infty} = 3{,}225$



$p_j/p_\infty = 8.7$
$m_j/m_\infty = 0.43$



$p_j/p_\infty = 16.2$
$m_j/m_\infty = 0.80$

(b) $M_\infty = 4.50$.

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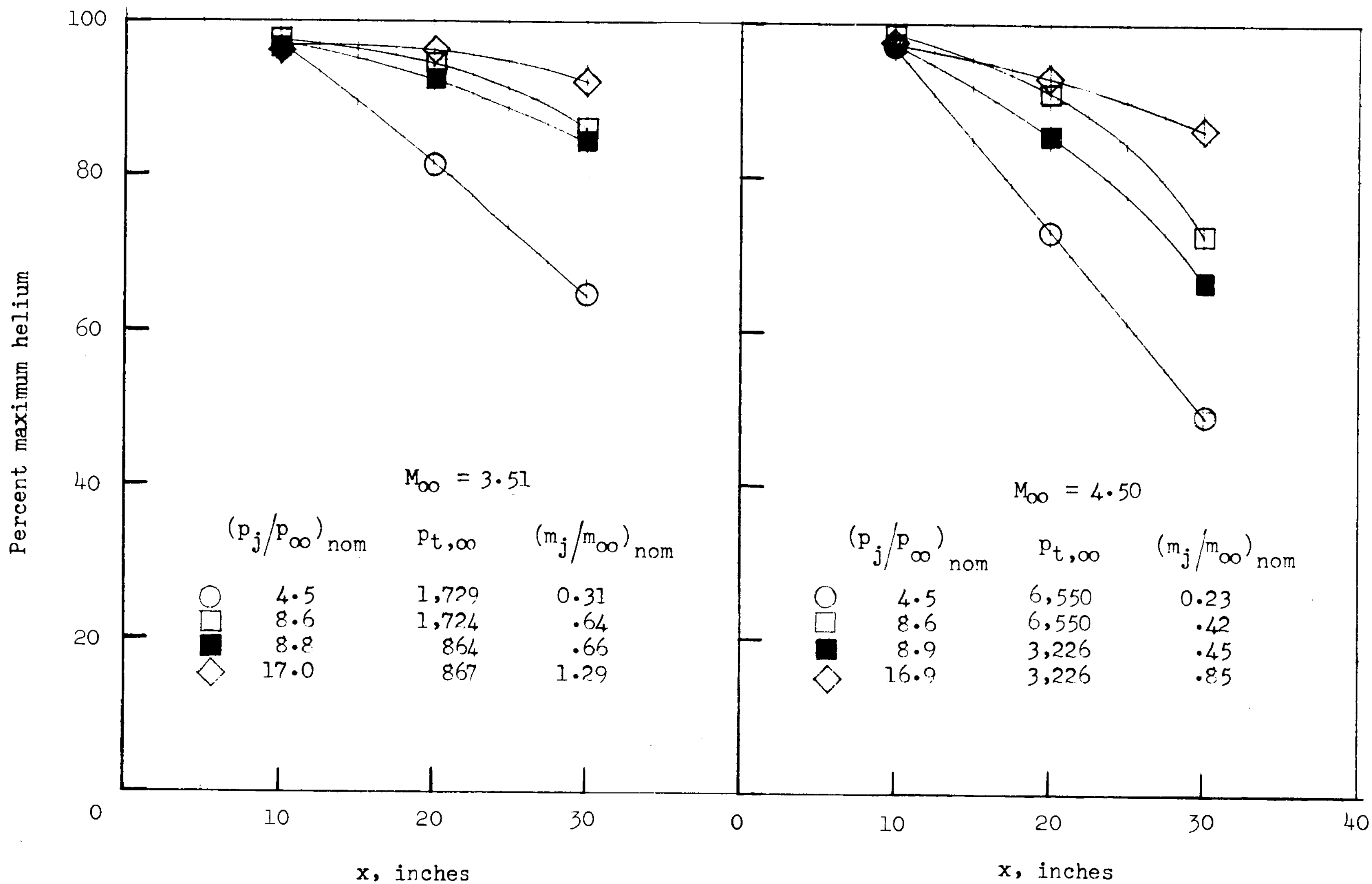
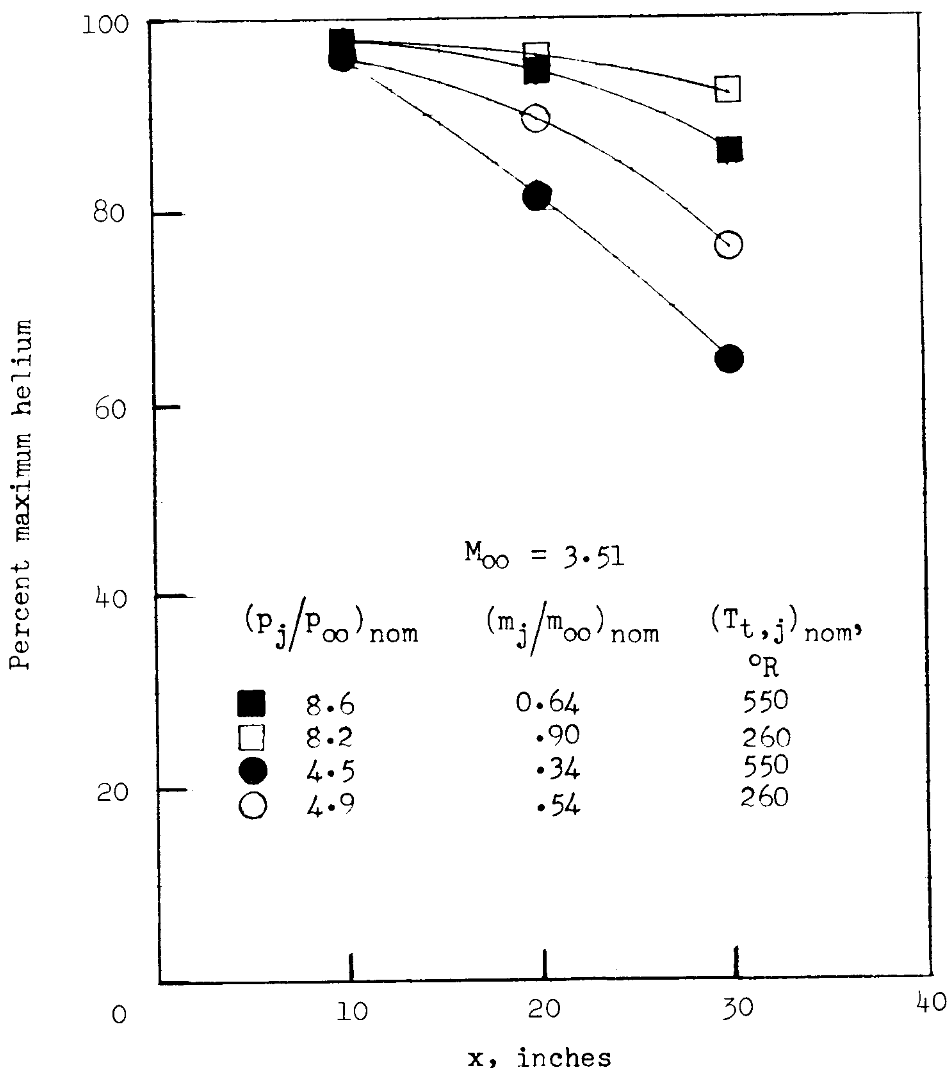
Figure 8.- Concluded.



(a) Effect of p_j/p_∞.

Figure 9.- Effect of p_j/p_∞ and $T_{t,j}$ on maximum measured helium concentrations in vertical plane at several axial stations downstream of vent.



(b) Effect of $T_{t,j}$.

Figure 9.- Concluded.

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